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Horizontal Variability of Ocean Skin Temperature from Airborne Infrared Imagery

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LONG-TERM GOALS

The long-term goal is to understand the mechanisms that produce spatial variability in ocean surface skin temperature over a wide range of scales under low wind conditions.

OBJECTIVES

The first objective is to use an airborne infrared imager to produce both overview maps and high-resolution time series of thermal variability over the CBLAST study area. The second objective is to combine these data with measurements by other investigators to determine the extent to which horizontal variability in surface temperature is related to atmospheric and sub-surface phenomena.

APPROACH

The approach is to make airborne measurements of horizontal variability of ocean surface skin temperature during the CBLAST-LOW experiments using two complementary infrared (IR) sensors. An IR imaging system provided high spatial and temporal resolution while a narrow field-of-view (FOV) radiometer system provided calibrated surface temperature. The high spatial coverage and fine spatial and temperature resolution of our systems allowed us to examine spatial scales in skin temperature from processes that span the atmospheric boundary layer of $O(1$ km$)$ down to wave-related processes $O(1$ m$)$. We produce synoptic maps of temperature covering the CBLAST-LOW region at moderate altitude as well as observations of fine-scale structures. Flight tracks allowed us to utilize the offshore tower (instrumented by J. Edson – WHOI [*Edson et al.*, 2004]) and horizontal ocean buoy array (deployed by R. Weller – WHOI [*Farrar et al.*, 2004]) data sets as well as directly compare sea-surface signatures with the oceanic and atmospheric boundary layer processes and fluxes. For the 2nd experiment in August/September of 2002 and the 3rd field campaign in July/August of 2003, we made measurements of the sea surface and the sky with down- and up-looking AIM model 640Q longwave (8-12 μm) IR imagers (512 x 640 pixels) and Heimann KT-15 radiometers (8-14 μm). A Pulnix digital video camera was implemented to characterize the sea surface condition.

WORK COMPLETED

We completed analysis on data taken during the CBLAST pilot experiment that occurred in July/August of 2001. These results have been submitted for publication to *Geoscience and Remote Sensing Letters* and presently the manuscript is accepted pending final revision [*Zappa and Jessup*, 2004a]. We analyzed data taken during the 2nd CBLAST experiment in August-September of 2002 and presented the results at the recent *AMS 16th Symposium on Boundary Layers and Turbulence* [*Zappa and Jessup*, 2004b]. A description of the airborne IR imagery system is given on the CBLAST-Low website (http://www.whoi.edu/science/AOPE/dept/CBLAST/CBLAST%20IR%20Description.htm). We participated in the 3rd and final CBLAST-Low experiment in July-August of 2003. The surveys in 2002 and 2003 quantified the horizontal mesoscale variability in the domain around the CBLAST-LOW site near the offshore tower and the horizontal ocean mooring/buoy array throughout the region extending 40-50 km offshore. Temperature maps from 2003 can be found on the CBLAST-Low website (http://www.whoi.edu/science/AOPE/dept/CBLAST/low/aircraft.html). The data have been cataloged and we have surveyed them for important results. We have quantified the SST variability and are beginning to determine the causes of the enhanced SST variability under low winds.

RESULTS

The IR imagery shows high temperature variability on scales of $O(10\text{ m} - 1\text{ km})$. Maps of sea surface temperature produced using the low-noise, high-resolution data from the longwave IR imager suggest that diurnal warming and tidal advection/mixing control the regional scales of SST. Results from the two weeks of flights in 2002 show that clear skies, strong insolation and moderate wind speeds lead to high SST variability (2.1°C in 10 km). The variability in SST is shown to diminish with the increase in overcast conditions and high wind speed events (1.5°C in 10 km). Measurements from 2003 show similar results with horizontal gradients reaching 4.5 °C in 10 km. Repeated flights give us the capability to track the diurnal variability of ocean surface temperature and allow us to determine the extent to which ocean mixing, advection, or heat flux variability is driving this temperature variability.

Not only do we observe regional variability that is important to air-sea fluxes, but we also observe small-scale structures within the IR imagery that suggest mechanisms that drive or enhance exchange under low wind speed conditions [*Zappa and Jessup*, 2004b]. The IR imagery shows high temperature variability on scales of $O(10\text{ m} - 1\text{ km})$. Figure 1 (Top) shows a mosaic of IR images that depicts a change in regimes of temperature variability across several large-scale temperature fronts. These data were taken in the afternoon on 8-14-03 at an altitude of 875 m, which corresponds to a resolution for the imager of roughly 0.9 m. The aircraft was heading south and the flight track was from left to right in the mosaic. The wind speed was roughly 3.4 m s^{-1} and the direction was from the West. An individual IR image is roughly 350 m x 450 m in scale, such that the mosaic is roughly 350 m x 5600 m. Lighter shades of gray are warmer temperatures. The variability in temperature across these large-scale fronts is observed in Figure 1 (Top) to be of $O(0.5\text{ °C})$ and the spatial scale between the fronts are of $O(1\text{ km})$. Figure 1 (Bottom) shows the temperature and derivative of the temperature along the track observed during the flight of the observed mosaic in Figure 1 (Top). A field of coherent parallel structures is observed in the IR imagery to the north of the front at 2700 m along the track showing spatial temperature variability to be 0.007°C m^{-1} and spatial scales of 21.7 ± 7.3 m. *Thorpe* [1988] observed similar coherent structures during stable stratification and suggested the positive skewness was due to "billows" from shear-induced turbulence. Here, the observed skewness is 2.8, which is significantly greater than that observed by *Thorpe* [1988]. Between 2700 m and 3500

m along the flight track, little variability exists and the gradient is calculated to be 0.002 °C m⁻¹. After crossing a sharp temperature front at 3500 m along the flight track, the gradient increased to 0.004 °C m⁻¹. In this example, distinct regime changes of the spatial variability of SST and their associated coherent structure occur across the passages of fronts.
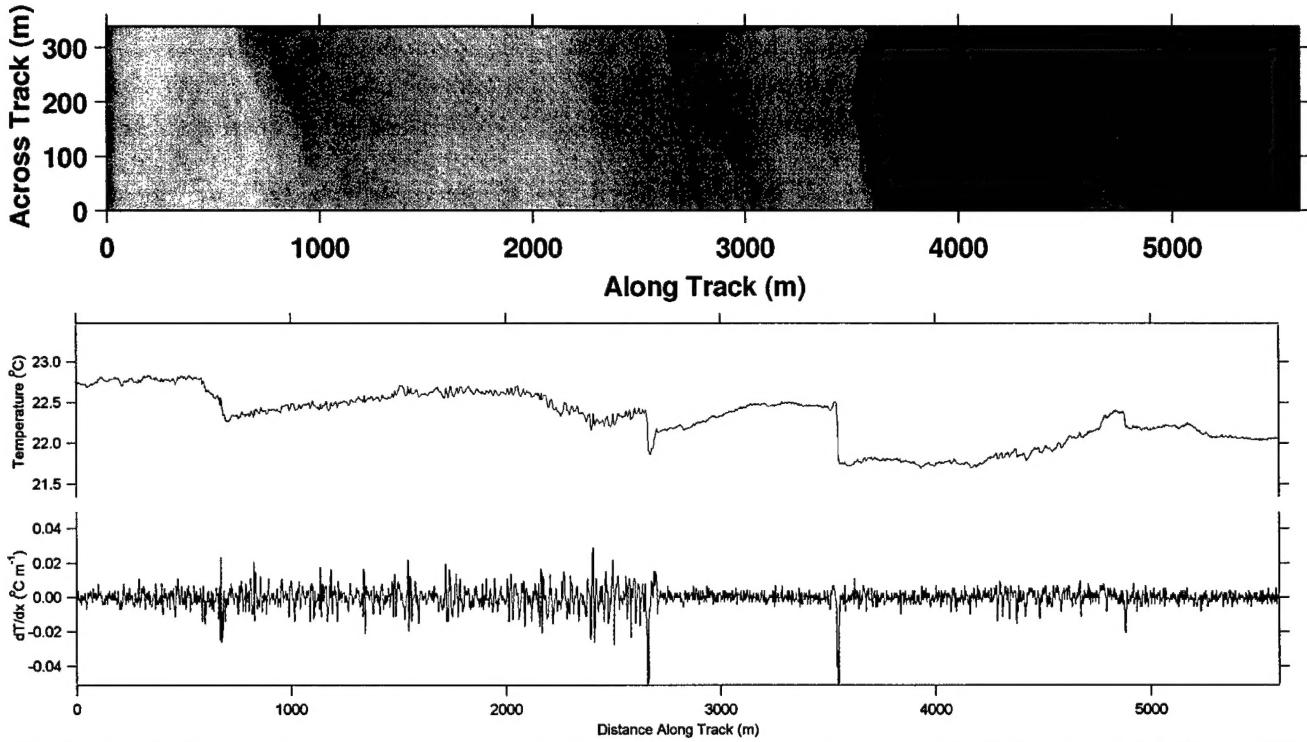

Figure 1. (Top) Mosaic of IR images showing a change in regimes of temperature variability across several large-scale temperature fronts observed on 8-14-03 during a period when the wind was 3.4 m s⁻¹ from the West. The top of the mosaic is East. (Bottom) Sub-Frame mode temperature and its derivative measured along the flight track.

We also observed fine-scale features within the IR imagery under very low up to moderate wind speed conditions. At wind speeds less than 1 m s⁻¹, the infrared imagery exhibits a broad range in scales of variability. Some regions show minimal structure where the spatial temperature variability is calculated to be 0.004 °C m⁻¹ and spatial scales of $O(100$ m$)$, while other regions show copious cold circular blotchy features where the spatial temperature variability is calculated to be 0.013 °C m⁻¹ and spatial scales less than of $O(10$ m$)$. The overall skewness was observed to be 0.06, suggesting that the temperature variability is Gaussian. The evolution of fine-scale features within the IR imagery during a moderate wind speed period increasing to 8 m s⁻¹ shows an ocean surface that is roughly uniform in temperature with very thin bands of cool water that are parallel to the wind and roughly 0.05°C less than the broad regions between the bands. The spacing between these thin cool bands is 28.6 ± 10.2 m. Here, the spatial temperature variability is calculated to be 0.005°C m⁻¹ and the overall skewness was observed to be 0.07, suggesting that the temperature variability is Gaussian. These parallel-aligned structures are suggestive of Langmuir circulation. The horizontal spacing of these features increased from 10 m up to 50 m with the increase in fetch offshore and coincided with wind-aligned surface slicks and bubbles visible in the video.

Fine-scale imagery of ocean skin temperature elucidated a variety of mechanisms related to atmospheric and sub-surface phenomena that produce horizontal variability over a wide range of scales. A summary of the mean fine-scale variability as a function of wind speed is shown in Figure 2,

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including all flights from the 2002 and 2003 field experiments. Figure 2 distinctly shows that the temperature variability decreases with increasing wind speed. Wind forcing increases near surface mixing that results in the breakdown of horizontal temperature gradients. The processes outlined above and shown in *Zappa and Jessup* [2004b] contribute to the fine-scale variability observed in Figure 2.
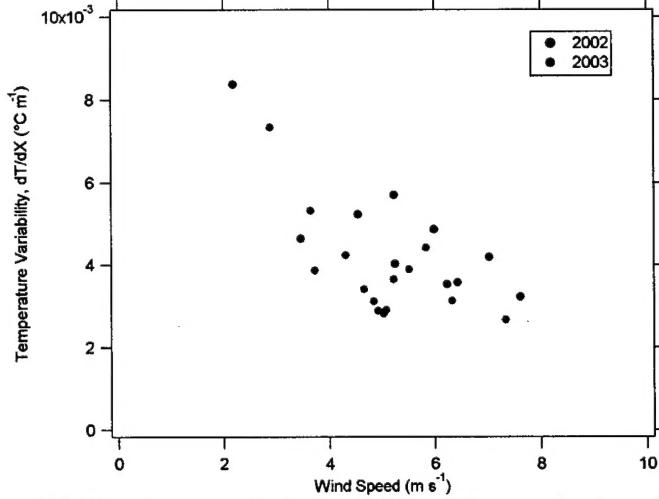

Figure 2. Mean fine-scale variability versus wind speed for each run during the CBLAST-Low experiments of 2002 and 2003.
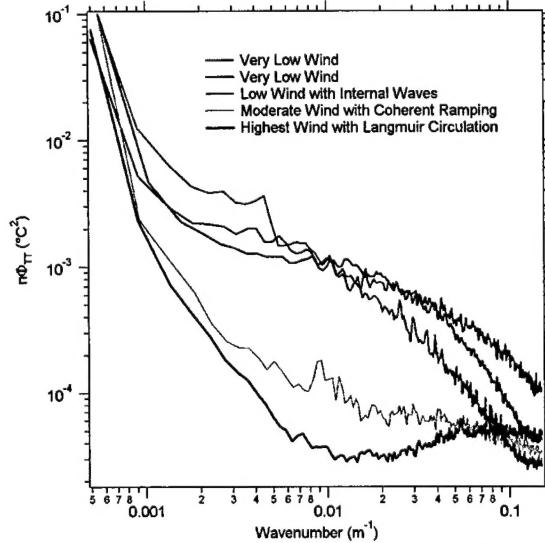
Figure 3. Variance-preserving wavenumber spectra of temperature from the infrared imagery for representative runs during the CBLAST-Low experiments of 2002 and 2003.

Spectra of the skin temperature give a more comprehensive view of the range in scales of fine-scale horizontal variability. Figure 3 shows the variance preserving wavenumber spectra of skin temperature measured from the IR imagery. Under low wind-speed conditions (0 to 2.5 m s^{-1}), the IR imagery shows high temperature variability on scales of O(1 m to 100 m) without the distinction of coherent structures. The spectra are characterized by a broad distribution of energy that decreases at high wavenumber with increasing wind speed. During one spectra at low wind, internal waves were present and a peak in the spectra occurred at a wavenumber of roughly 0.004 m^{-1}, that of the peak wavenumber for the internal waves. During moderate winds (2.5 to 5 m s^{-1}), we observed extensive

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regions (O(1 km)) of closely-spaced (O(10 m)) successive sharp coherent temperature ramps of O(1°C) that coincide with ubiquitous visible surface slicks parallel to the fronts. For the specific example in Figure 3, the variability in temperature across these successive fronts for this run is of O(0.5 °C) and the spatial scale between the crests of the fronts are roughly 88 ± 17 m. The spectra exhibit a significant energy drop at intermediate wavenumbers with a peak in wavenumber at roughly 0.01 m^{-1}, the scale of the coherent ramping structures. For wind speeds greater than 5 m s^{-1}, the data show significantly less temperature variability with a high incidence of breaking waves and distinct row/streak structures in the IR imagery that were aligned with the wind and were likely the surface manifestation of Langmuir circulation cells. Here, the energy in the spectra dips at intermediate wavenumbers but increase at higher wavenumber in the range 0.05 to 0.1 m^{-1}, the scales of observed Langmuir circulation.

One question that can begin to be addressed is whether this horizontal spatial temperature variability is accompanied by similar subsurface vertical temperature structure. Figure 4 shows the mean fine-scale variability as a function of the near surface stratification defined by the Brunt-Vaisala frequency, N^2. In this case, N^2 is a measure of the vertical near-surface temperature gradient since salinity was assumed to be constant. The temperature variability increases with near surface stratification under conditions when the atmospheric boundary layer is stable (z/L = 0.0 to 0.7). For the lone case when the atmospheric boundary layer is unstable (z/L = - 0.2), the temperature variability attains the largest value and does not follow this linear relationship. This may be due to an extremely shallow stratified layer that developed under this low wind speed case or due to similar features that have been observed under unstable cases of convective mixing [*Zappa et al.*, 1998]. Regardless, the results suggest that the horizontal temperature variability is closely tied to the vertical near-surface temperature stratification under stable atmospheric conditions.
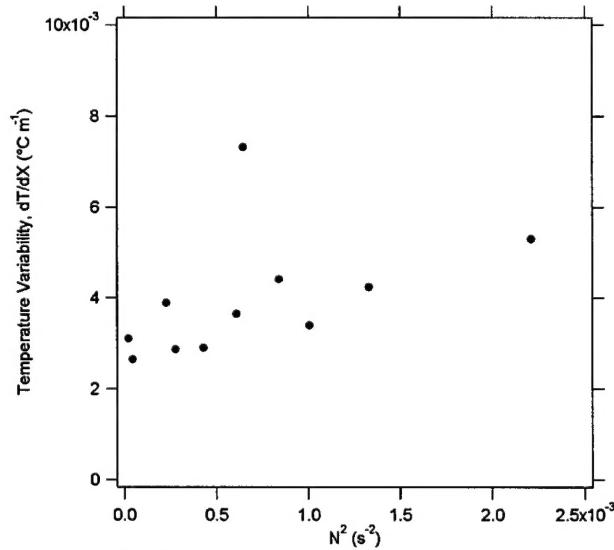

Figure 4. Mean fine-scale variability versus near surface stratification defined by the Brunt-Vaisala frequency for each run during the CBLAST-Low experiments of 2003.

IMPACT/APPLICATIONS

The encouraging results of our airborne deployments under the CBLAST DRI demonstrate that we are able to provide sea surface temperature measurements with high spatial resolution and accuracy. The impact of our analysis and observations will be to show that remote sensing techniques can quickly

characterize the spatial and temporal scales of a wide variety of processes that are important to the air-sea fluxes, as well as to relate the fine-scale to the larger-scale variability.

TRANSITIONS

None

RELATIONSHIP TO OTHER PROGRAMS OR PROJECTS

This project is in collaboration with A.T. Jessup of the Applied Physics Laboratory at the University of Washington. We are working closely with R. Weller of WHOI to correlate the IR signatures with environmental conditions measured by the buoys deployed during CBLAST and at the ASIT tower.

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Zappa, C.J., and A.T. Jessup, High resolution airborne infrared measurements of ocean skin temperature, *Geoscience and Remote Sensing Letters*, 2004 [in press, refereed].

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